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Ultrashort pulse inscription of photonic structures in ZnSe and GaAs for mid infrared applications

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14. ABSTRACT

Over the past year, channel waveguide technology in ZnSe and Cr2+: ZnSe has undergone major advancement from initial low loss guiding in the near-infrared to mid-infrared with single or multimode behaviour. These structures have been used in waveguide cavities and provided the first demonstration of a channel waveguide laser, paving the way to the development of high power, compact and robust Cr2+: ZnSe sources. Initial results of 5% slope efficiency and 18.5 mW outputs have already been improved by almost a factor of 3 to 14% and 43 mW and far greater performance is expected through waveguide optimisation and access to greater pump powers. Single pass amplifier internal gain has been measured at 3.4 dB with maximum performance only limited by the available pump power (1.2 Watts).

The results contained in this report complete Phase 2 of the project with a number of successful outcomes, realising compact, channel waveguide sources in Cr2+: ZnSe. This sets solid foundations for the project to progress to Phase 3 and the development of high power, robust mid-infrared waveguide sources for real world applications.

15. SUBJECT TERMS

EOARD, low loss waveguides in ZnSe, laser inscription in bulk materials, mid infrared sources, advanced short pulsed laser material, fabrication of waveguides inside ZnSe, Cr2+: ZnSe and Fe2+: ZnSe, directly written mid infrared waveguide laser

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September 2012

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Project Milestones

Throughout the course of this project a number of major milestones have been achieved. The first permanent refractive index change in ZnSe using ultrafast laser inscription was attained. Previous investigations carried out by various other research groups had proven unsuccessful in affecting any observable subsurface damage or refractive index change in a ZnSe substrate. After our initial investigations the reason for this difficulty was attributed to the high third order nonlinearity of the ZnSe crystal. In order to overcome nonlinear effects detrimental to the inscription process, the project pioneered the application of pulse duration as a key variable in ultrafast laser inscription and obtained a localized increase in material refractive index. Following this milestone, the first directly written low loss near-infrared waveguides were fabricated in a ZnSe substrate. This body of work was published as a letter in Optics Letters [1].

Further investigations into the laser inscription parameters yielded the first localized reduction in the refractive index of ZnSe. This significant result allowed the fabrication of depressed cladding waveguides with their cross-sections tailored to obtain mid-infrared wave guiding. This technology was then applied to Cr: ZnSe substrates and waveguides were built into a compact laser cavity and demonstrated the first waveguide Cr: ZnSe laser as well as the longest wavelength laser source ever fabricated through ultrafast laser inscription. The Cr: ZnSe waveguide laser operated at 2573 nm with a maximum output power of 18.5 mW with 5% slope efficiency for a 1928 nm pump power of 1.2 W. This exciting result paves the way to power scaling current Cr: ZnSe sources and offers the prospect of a host of compact, integrated mid-infrared photonic devices. The achievement of lasing in a Cr: ZnSe waveguide has been submitted to Applied Physics Letters journal and is currently under consideration for publication.

A significant improvement in Cr: ZnSe waveguide laser performance was achieved through the development of a circular cross-section depressed cladding waveguide. A compact laser cavity was constructed using these new waveguides and demonstrated laser operation at 2486 nm with a maximum output power of 43 mW for 1.2 W of pump power and a maximum slope efficiency of 14%. The amplification properties of the circular cross-section waveguides was investigated, yielding a single pass internal gain as high as 3.4 dB for a 6 mm waveguide.

Following the production of this report, a substantial improvement in Cr: ZnSe waveguide laser performance has been demonstrated. The circular cross-section depressed cladding waveguide structures have been constructed into laser cavities and exhibited output powers of 285 mW with a 45% slope efficiency for 1.11 W of pump power. This corresponds to an optical to optical efficiency of 26%. These new results have been submitted for publication in Optics Letters and will be included in an accepted presentation at CLEO-Pacific Rim 2013. A full list of publications is shown below followed by the final report produced in September 2013:

List of publications to date

1) J. R Macdonald, R. R. Thomson, N. D. Psaila, S. J. Beecher, H. T. Bookey, A. K. Kar, "Ultrafast laser inscription of low loss waveguides in polycrystalline ZnSe," *IEEE Photonics Society, 2010 23rd Annual Meeting of the* , vol., no., pp.56-57, 7-11 Nov. 2010

2) J. R. Macdonald, R. R. Thomson, S. J. Beecher, N. D. Psaila, H. T. Bookey, and A. K. Kar, "Ultrafast laser inscription of near-infrared waveguides in polycrystalline ZnSe," Optics Letters, **35**, 4036-4038 (2010).

3) P. A. Berry, J. R. MacDonald, A. K. Kar, and K. L. Schepler, "Ultrafast Laser Inscription of Waveguide Structures in Cr2+:ZnSe," in *Advances in Optical Materials*, OSA Technical Digest (CD) (Optical Society of America, 2011), paper AIFB5.

4) J. R. Macdonald, P. A. Berry, K. L. Schelper, and A. Kar, "Directly Written Mid-Infrared Waveguides in Zinc Selenide," in *Lasers, Sources, and Related Photonic Devices*, OSA Technical Digest (CD) (Optical Society of America, 2012), paper IF1A.3.

5) J. R. Macdonald, S. J. Beecher, P. A. Berry, K. L. Schepler, and A. K. Kar, "Compact Mid-Infrared Cr: ZnSe Channel Waveguide Laser," Appl. Phys. Lett., doc. ID L13-00523 (posted 00514 March 02013, in press) (2013).

6) J. R. Macdonald, S. J. Beecher, P. A. Berry, K. L. Schepler, and A. K. Kar, "Mid-Infrared Cr:ZnSe Channel Waveguide Laser," CLEO-PR&OECC/PS, Accepted (2013).

7) J. R. Macdonald, S. J. Beecher, P. A. Berry, K. L. Schepler, and A. K. Kar, "Efficient mid-infrared Cr:ZnSe channel waveguide laser operating at 2486 nm," Optics. Lett., doc. ID: 188537 (posted 10th April 2013) (2013).

Contents

1. Introduction

Sources in the mid-infrared region (2-5 μm) are in high demand across a wide range of disciplines due to the atmospheric transmission window and the location of many organic and inorganic molecular absorption lines. Applications such as infrared countermeasures, remote sensing, communications and non-invasive imaging utilise sources in this spectral region and continue to drive research into compact and robust mid-infrared lasers.

Transition metal doped II-VI semiconductors such as Cr^{2+}: ZnSe, Cr^{2+}: ZnS and Cr^{2+}: CdSe have demonstrated many desirable properties such as large bandwidths for absorption and emission, large emission cross-sections, no excited state absorption and room temperature operation [1-4]. In particular, Cr^{2+}: ZnSe lasers have demonstrated room temperature CW output powers of 14 W [5], gain switched pulsed operation at 18.5 W [6] and continuously tunable CW output from 1973-3339 nm [7]. Despite these promising advancements, the power scaling of II-VI chromium lasers has long been held back by the high thermo-optic coefficient of the host materials [3]. A waveguide geometry offers an attractive solution to this problem by substantially reducing the effect of thermal lensing within the gain medium [8]. Furthermore, the compact and vibration insensitive nature of waveguide lasers is ideally suited to the aforementioned applications. ZnSe fibres have been fabricated with low propagation losses [9], but to date there have been no published results with Cr^{2+} doping.

Ultrafast laser inscription offers unique capabilities in the fabrication of low-loss channel waveguides in that it allows rapid prototyping, fabrication of truly 3-D architectures and is highly flexible across a wide range of different glass and crystal substrates [10-13]. The first phase of the project successfully developed the first directly written near-infrared waveguides in ZnSe and Cr^{2+}: ZnSe [14, 15]. This report details the substantial progress over the last year and details the achievement of multiple milestones including mid-infrared waveguides in ZnSe and the demonstration of the first channel waveguide laser in Cr^{2+}: ZnSe.

2. Ultrafast laser inscription

Ultrafast laser inscription relies on focusing ultrashort pulses of sub-bandgap radiation inside the substrate material. The high irradiances present in the focal volume induce nonlinear

absorption phenomena that deposit optical energy in the form of a free-electron plasma. Following this, the plasma transfers energy to the material lattice, a transfer that may induce localized structural modifications. These modifications can manifest themselves in many ways, including a change in refractive index. If the refractive index modification is appropriately controlled, waveguides can be directly inscribed inside the material by translating it through the laser focus. A graphical representation is shown in Figure 1.

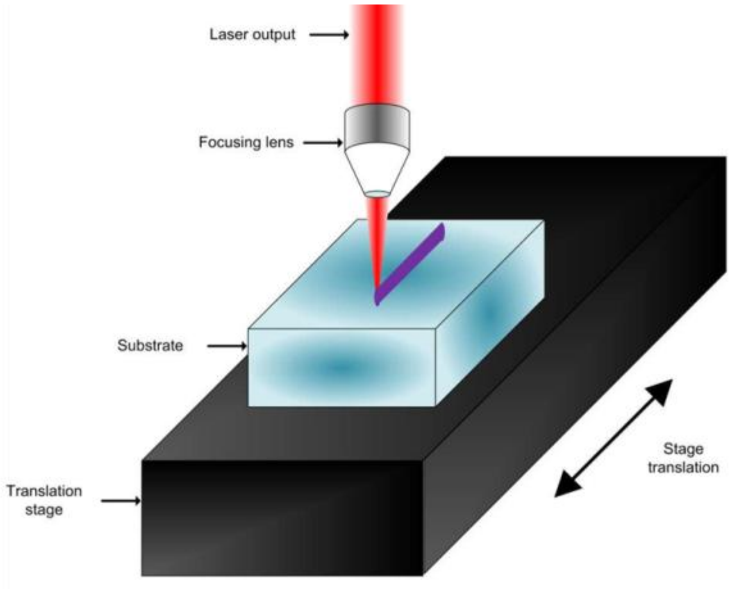

Figure 1. Graphical representation of ultrafast laser inscription of waveguides in a dielectric substrate.

Over the past decade, this technique has proven a highly flexible tool for the fabrication of a host of active and passive photonic devices in single crystal, ceramic and glass substrates. This range of devices span applications such as: astrophysics [16, 17], compact laser sources [18, 19], biophotonics and lab-on-chip technology [20, 21], sensors [11], and integrated photonics [10, 22].

At Heriot-Watt, ultrafast laser inscription of devices is performed with our state-of-the-art inscription apparatus which utilises a chirped pulse amplified, fibre MOPA (Master Oscillator Power Amplifier) system as the inscription laser (IMRA µJewel D400). This system incorporates computer control over power and polarisation and nanometer resolution XYZ airbearing stages (Aerotech) for translation of the sample substrate. Figures 2 - 4 show the arrangement of this apparatus.

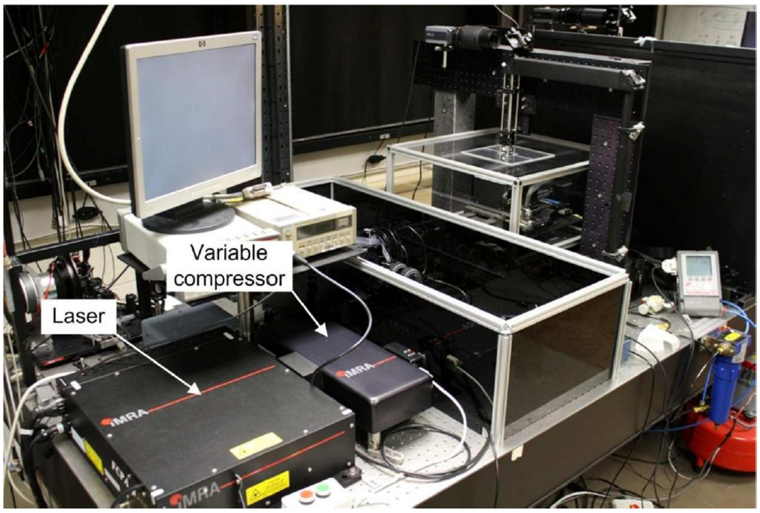

Figure 2. Ultrafast laser inscription apparatus: IMRA inscription laser and variable compressor

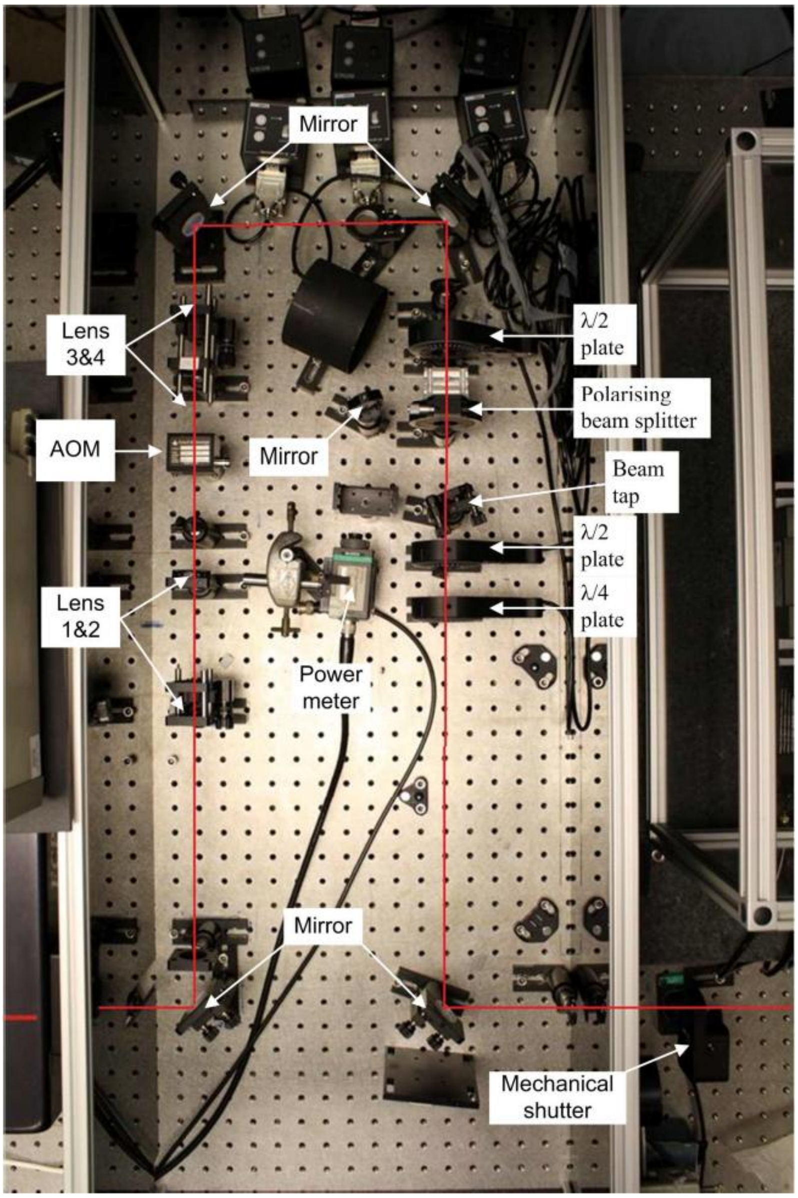

Figure 3. Ultrafast laser inscription apparatus: Power and polarisation control.

The external variable compressor (see Figure 2) allows the adjustment of the pulse duration used for inscription. Previous work on this project has highlighted this as an essential capability when working with highly non-linear materials such as ZnSe [14], and this technique has been pioneered by the project over the last three years. The acousto-optic modulator (AOM) is included in the apparatus to allow rapid modulation of the inscription beam for the fabrication of periodic features such as Bragg gratings [22].

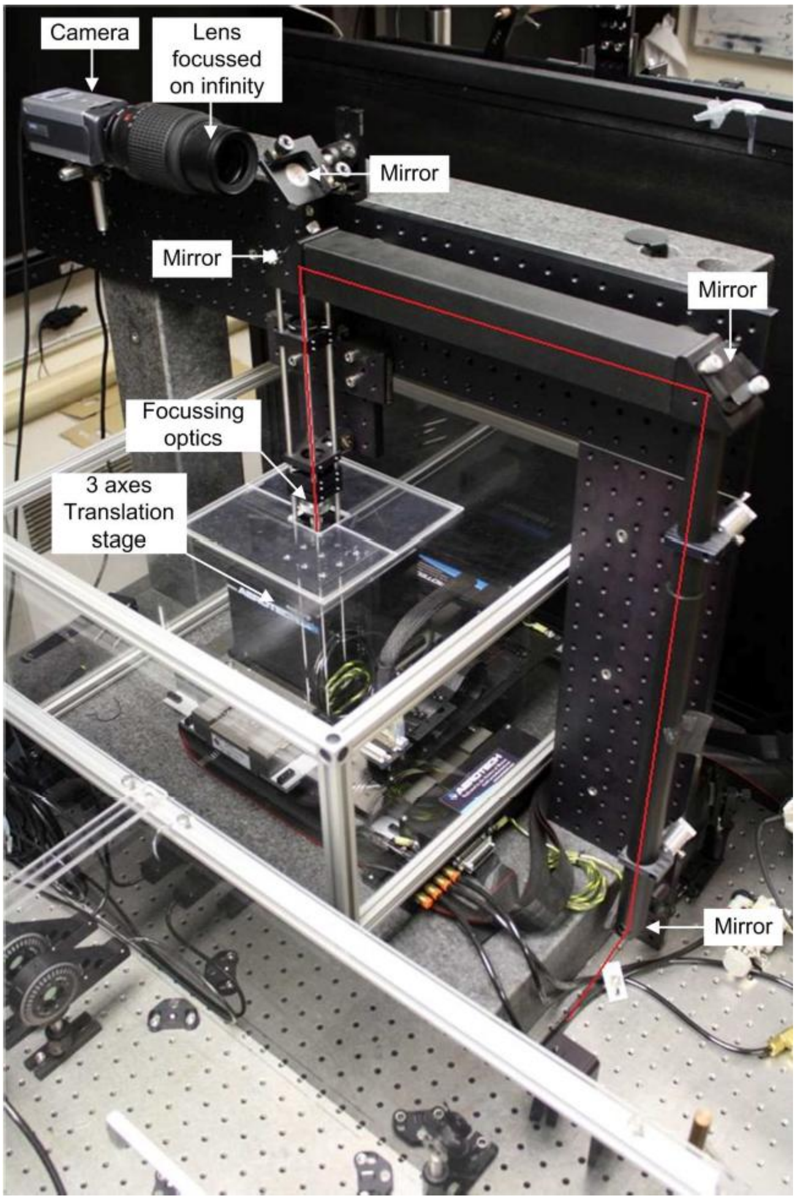

Figure 4. Ultrafast laser inscription apparatus: IMRA inscription laser beam path, focusing optics and imaging system.

An important waveguide inscription procedure utilised throughout this project is the multiscan technique [23, 24]. This technique allows the tailoring of waveguide cross-section as well as a higher degree of control over the energy deposition within the desired waveguide volume. By overlapping multiple scans with asymmetric focal volumes, a symmetrical modified region can be created as illustrated in Figure 5.

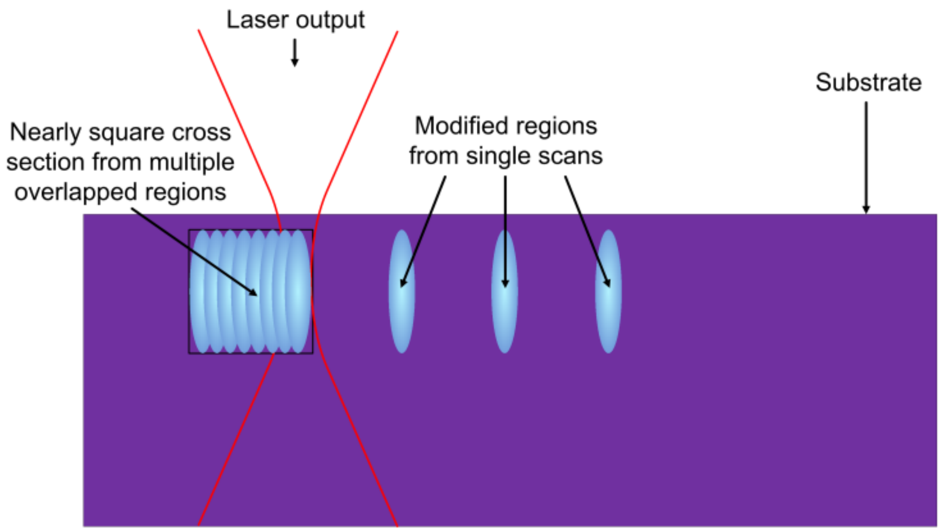

Figure 5. Multiscan technique inscription geometry. Overlapping scans are used to fabricate one near-symmetrical modified region.

3. Mid-infrared waveguides in ZnSe

Ultrafast laser inscription offers a versatility that allows the fabrication of various waveguide structures. Conventional laser inscribed waveguides consist of a core of modified material with increased refractive index which is surrounded by unmodified material, however other waveguide designs exist.

3.1. Core-written waveguides

The successful fabrication of near-infrared waveguides in Cr^{2+}: ZnSe was a major milestone in this project, but the requirement for mid-infrared waveguides, capable of guiding wavelengths within the emission range of Cr^{2+}: ZnSe (~ 2-3 μm), demanded structures with either a larger cross-sectional area or greater refractive index contrast. Figure 6 shows the end facet of a near infrared waveguide inscribed in Cr^{2+}: ZnSe.

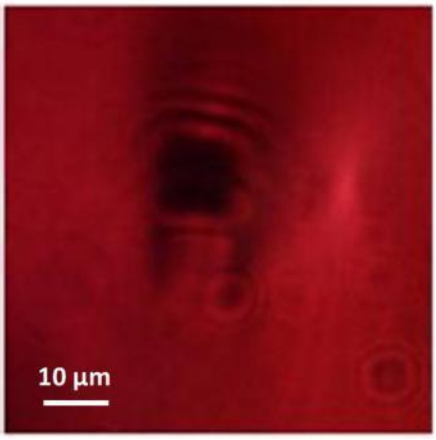

Figure 6. End facet of near infrared waveguide in Cr^{2+}: ZnSe. Field of view is 40 x 40 μm. Image acquired by optical microscope in transmission mode with white light illumination.

The structure in Figure 6 features a rectangular cross-section increase in refractive index, where the waveguide mode is supported, with a negative change to the refractive index above. Low-loss guiding of near infrared (1550 nm) was achieved in these structures but when moving to longer wavelengths the guided mode increasingly overlaps with the damage region and losses dramatically increase. This negative index change, damaged region, prevented any successful scaling of the waveguide cross-section in the vertical axis due to the persistent presence of the negative index change region. Attempts to increase the index contrast resulted in increased material damage. For the fabrication of waveguides for longer wavelengths a new inscription technique was therefore required.

3.2. Depressed cladding waveguides

Further investigation of inscription parameters yielded a negative refractive index change with little damage surrounding the modified region, Figure 7(a). This modification regime was achieved using higher pulse energies of ~500 nJ compared to the positive refractive index modification that required < 200 nJ pulses. Using the negative refractive index change, a depressed cladding structure was designed and fabricated in undoped ZnSe. The structure was shown to support guiding at 3.39 μm, the long wavelength limit of the Cr^{2+}: ZnSe emission band, with propagation losses of 1.9 $dB \cdot cm^{-1}$. The structure and 3.39 μm mode field are shown in Figure 7(c).

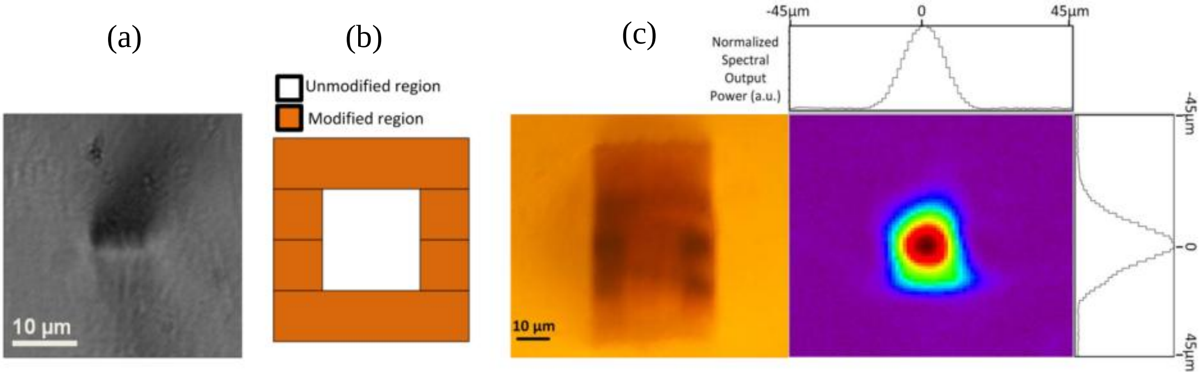

Figure 7. (a) Image of negative refractive index change in ZnSe taken using an optical microscope in transmission mode with white light illumination. (b) Map of depressed cladding waveguide design using the negative refractive index change. (c) Depressed cladding waveguide in ZnSe and associated guided mode at 3.39 μm.

This significant advancement was reported at the Advances in Optical Materials 2012 (AIOM) conference [25], and allowed work to progress to the inscription of mid-infrared waveguides in Cr^{2+}: ZnSe, milestone 4 in the project.

4. Phase 2 - Milestone 4: Fabricate waveguides in Cr2$^+$: ZnSe (1st October 2011 – 31st March 2012).

Waveguide inscription in Cr^{2+}: ZnSe was carried out using the parameters ascertained from the previous work in ZnSe. However, the initial structures showed distinct differences from the results obtained in the undoped ZnSe material, Figure 8. In order to compensate for this discrepancy, a slight adjustment of inscription parameters for Cr^{2+}: ZnSe was required.

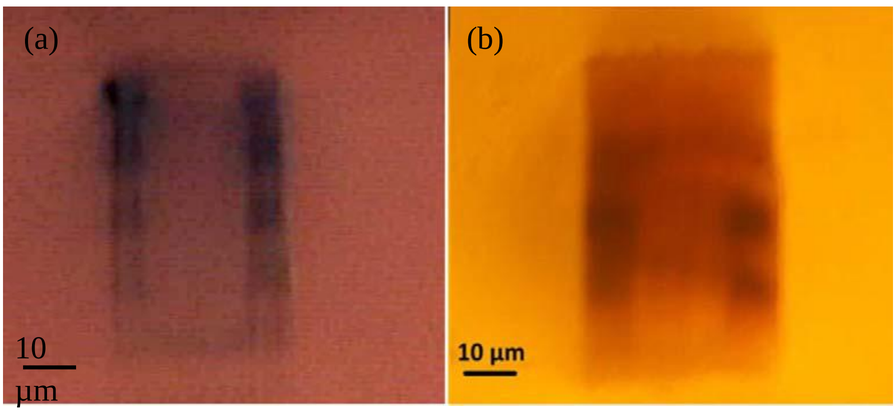

Figure 8. Waveguide end facet cross-section of structures written with the same inscription parameters in (a) Cr^{2+}: ZnSe and (b) undoped ZnSe. Field of view of both images is 90 x 90 μm.

4.1. Cr^{2+}: ZnSe modification

To minimise material waste of Cr^{2+}: ZnSe a parameter comparison was carried out with smaller areas of modification (~ 100 μm^2). Figure 9 shows a comparison of the modification between undoped ZnSe and Cr^{2+}: ZnSe. Such comparisons across a range of different inscription conditions allowed the selection of appropriate parameters for inscription in the doped media.

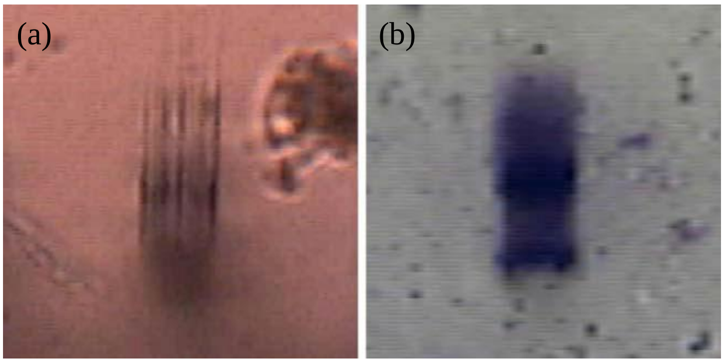

Figure 9. Example comparison of modification features in (a) Cr^{2+}: ZnSe and (b) ZnSe. Comparisons were drawn across a broad range of inscription parameters. Field of view in both images is 100 x 100 μm.

4.2. Mid-infrared waveguides in Cr^{2+}: ZnSe

Using these inscription parameters, waveguides were fabricated in Cr^{2+}: ZnSe. The initial structures displayed propagation losses too large for use in a waveguide laser cavity so a double, depressed cladding structure was conceived to improve performance, Figure 10. This design implemented a secondary outer wall, inscribed with greater pulse energies in order to reduce tunnelling losses for the waveguide. The inscription of the inner cladding wall was unchanged from previous structures in order to preserve the desirable features of a low refractive index contrast such as single mode like performance and low scattering losses.

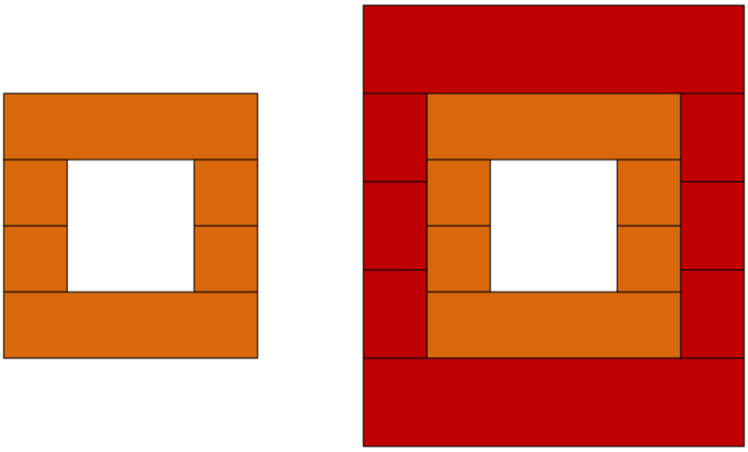

Figure 10. A schematic of (Left) a single clad and (Right) a double clad depressed cladding waveguide where the red colour represents a greater change in refractive index than orange.

The resultant structures demonstrated guiding at both the pump wavelength, 1.92 µm, and the long wavelength limit of the Cr^{2+}: ZnSe emission band, 3.39 µm. The near field images of these modes are shown in Figure 11.

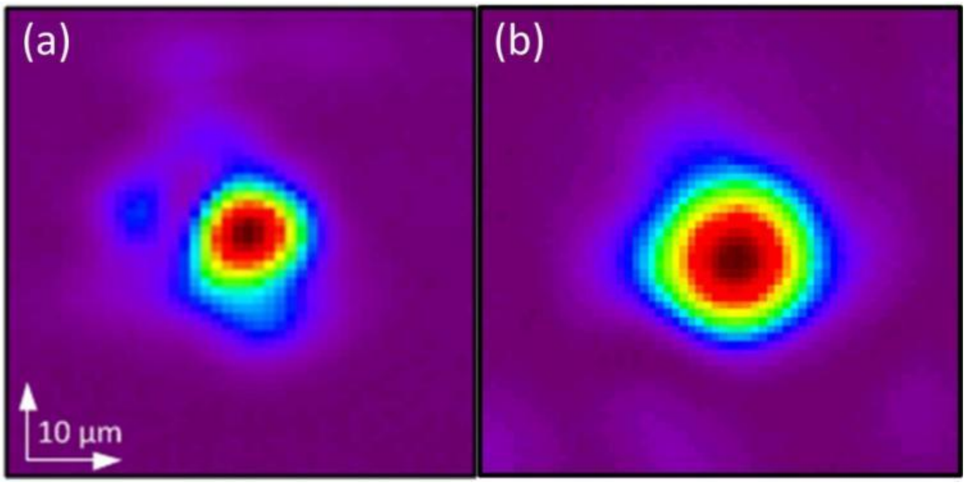

Figure 11. (a) Near-field image of the 1920 nm waveguide mode. (b) Near-field image of the 3392 nm waveguide mode, showing wavelengths beyond the emission band of Cr^{2+}: ZnSe are also guided by the structure. The field of view for both (a) and (b) is 60 µm horizontal, 50 µm vertical.

4.3. Milestone 4: Fabricate waveguides in Cr^{2+}: ZnSe conclusions

Waveguides have been fabricated in Cr^{2+}: ZnSe capable of guiding light in both the pump and signal wavelength range required for laser operation across the bandwidth of the Cr^{2+}: ZnSe emission cross-section. The demonstration of guiding at 3.39 µm shows the potential for continuously tunable laser operation across a wide range of the emission bandwidth as the waveguide cavity will be capable of supporting guiding across this broad wavelength range. This achievement marks the completion of milestone 4 in this project and allows work on milestone 5 to commence.

5. Phase 2 – Milestone 5: Demonstrate lasing in Cr^{2+}: ZnSe (1st April 2012 - 30th September 2012).

With waveguides capable of guiding both the pump and signal wavelength, the next stage was to construct a laser cavity.

5.1. Cr^{2+}: ZnSe waveguide laser

The waveguide structures described above in Section 4.2 were built into a compact cavity by butt-coupling a dichroic mirror on the input side of the waveguide and an output coupler mirror on the opposite side with optical coupling compound at waveguide-mirror interfaces. The dichroic mirror was anti-reflection coated for the pump wavelength and highly reflective for 2050-2430 nm. The output coupler was 80% reflective for a wavelength range of 1700–2700 nm. The cavity was pumped at 1928 nm with a continuous wave thulium fibre laser in the configuration shown in Figure 12(a). Continuous wave lasing was observed and a monochromator measured the wavelength peak of the laser emission to be at 2573 nm. The mode profile was measured by imaging the waveguide facet on to an infrared camera. These results are displayed in Figure 12.

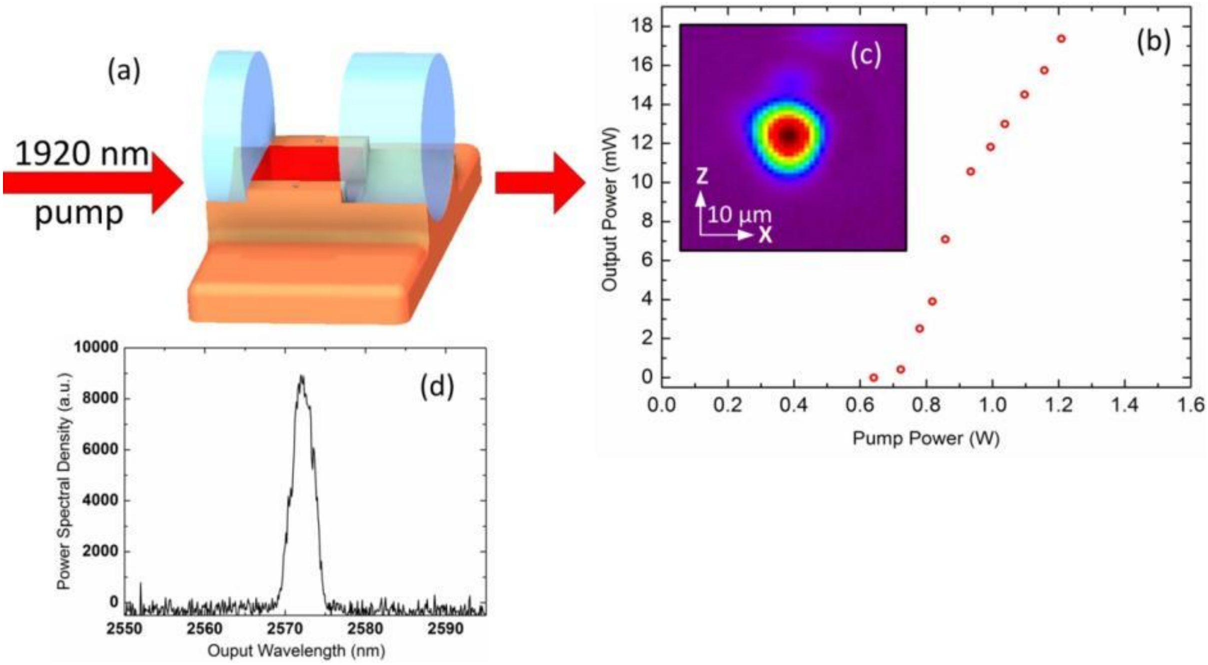

Figure 12. (a) Waveguide laser cavity assembly with butt-coupled dichroic mirror and output coupler mirror. (b) Laser output power against input pump power. (c) Near field image of the laser output mode at 2573 nm. (d) Laser output power spectral density.

The waveguide laser displayed a maximum output power of 18.5 mW for an incident pump of 1.2 W. A slope efficiency of 5% and pump threshold power of 700 mW were observed. This result is a major milestone in the project and also the field of mid-infrared photonics and as such the initial report of lasing in a Cr^{2+}: ZnSe channel waveguide has been submitted for publication as a Letter in Nature Photonics.

5.2. Cr^{2+}: ZnSe waveguide laser development

The demonstration of lasing in a Cr^{2+}: ZnSe channel waveguide is a highly significant development towards the power scaling of transition metal doped II-VI semiconductor materials. Upon inspection of the double clad waveguide structures under an optical microscope, significant cracking in the material was observed. The extent of this cracking is shown in Figure 13. In order to improve upon the results described in Section 5.1, it was necessary to reduce cracking within structures in order to decrease the propagation losses of the waveguides and consequently reduce laser threshold. A wide range of parameters were explored in order to lessen the extent of cracking in the structure. The parameters investigated included the separation of the multiscan blocks illustrated in Figure 10, the separation of the

individual scan elements, inscription pulse energy and the translation speed of the sample substrate.

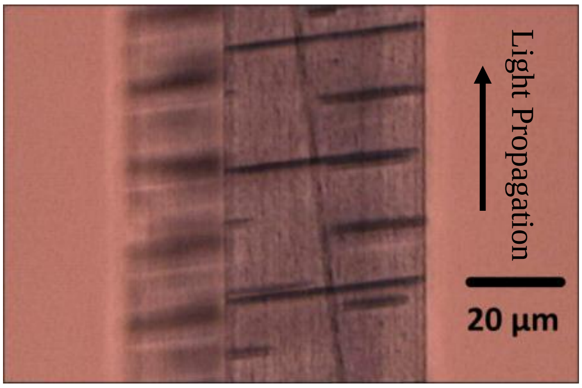

Figure 13. Optical microscope image from above waveguide displaying cracks in the material. The arrow indicates the direction light would propagation through the structure.

Low propagation loss laser inscribed waveguides in YAG (Yttrium Aluminium Garnet) based gain media have been demonstrated employing a circular cross-section depressed cladding waveguide [19, 26]. Through utilising our previously determined inscription parameters (Section 4.2), a similar circular cross-section waveguide was fabricated in Cr^{2+}: ZnSe, Figure 14. However, in order to achieve sufficient change in the refractive index, each inscription scan had to be overwritten. The number of overwrites on a single inscription scan was taken as a variable parameter and structures were investigated with 1 – 50 overwritten scan elements.

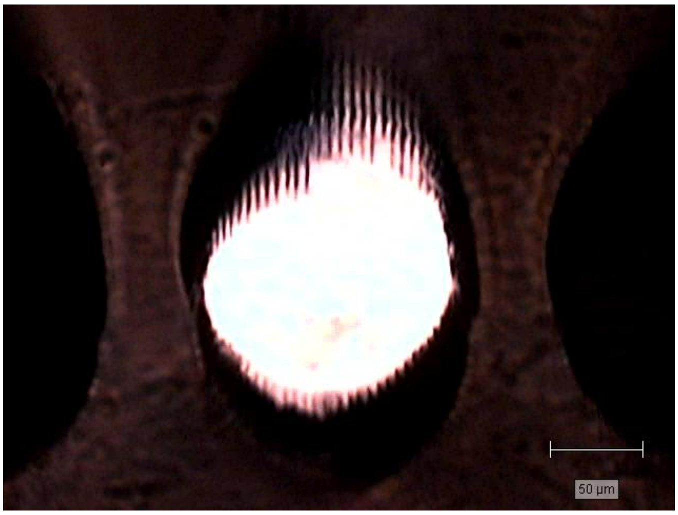

Figure 14. End facet of circular cross-section depressed cladding waveguide. Image taken with an optical microscope in transmission mode with white light illumination coupled into waveguide using a condenser lens.

It can be seen that these structures displayed some asymmetry in their cross-section and despite not being fully optimised demonstrated improved laser performance compared to the double clad waveguides. The waveguides were built into a cavity in the same manner as before (detailed in Section 5.1) with output couplers of 80%, 70% and 18% reflectivity, where the 18% reflectivity is achieved with only the Fresnel reflections off the end facet of the waveguide. Figure 15 shows the spectral output of the laser with a peak in its power spectral density at 2486 nm and a full width half maximum (FWHM) linewidth of 2 nm.

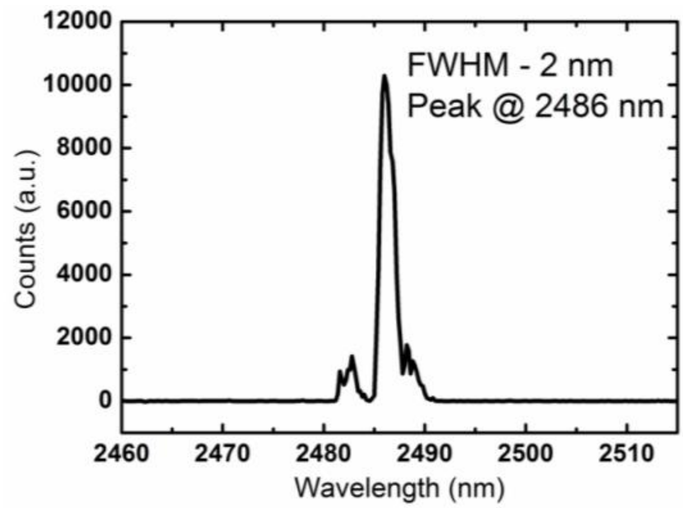

Figure 15. Laser output spectral density measured with a 300 mm monochromator showing a peak at 2486 nm.

Figures 16-18 show the laser input-output characteristics with each output coupler. The maximum slope efficiency recorded was 14% and was achieved with no output coupler (Fresnel reflections only). As expected, the 80% reflectivity output coupler demonstrated the lowest threshold, at 190 mW. The maximum output power recorded was 43 mW, although this is likely to be limited by our maximum available pump power.

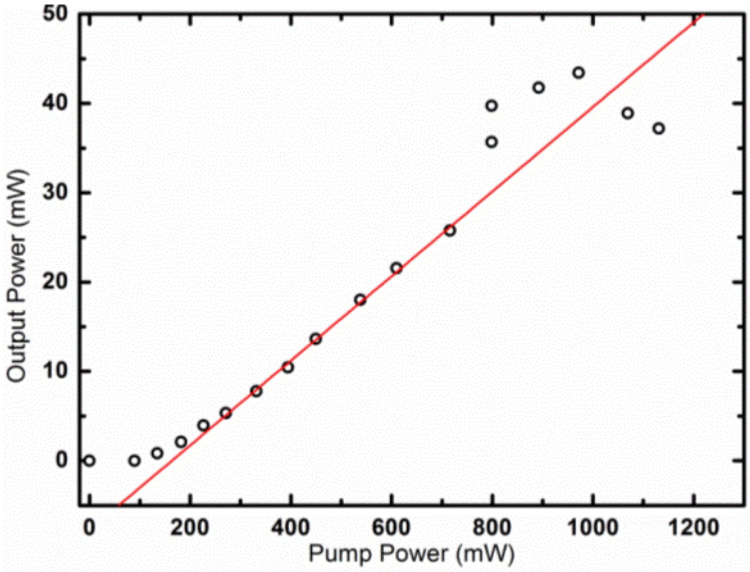

Figure 16. Laser output power as a function of pump power using an 80% reflectivity output coupler. Slope efficiency from fitted line is 4.7%.

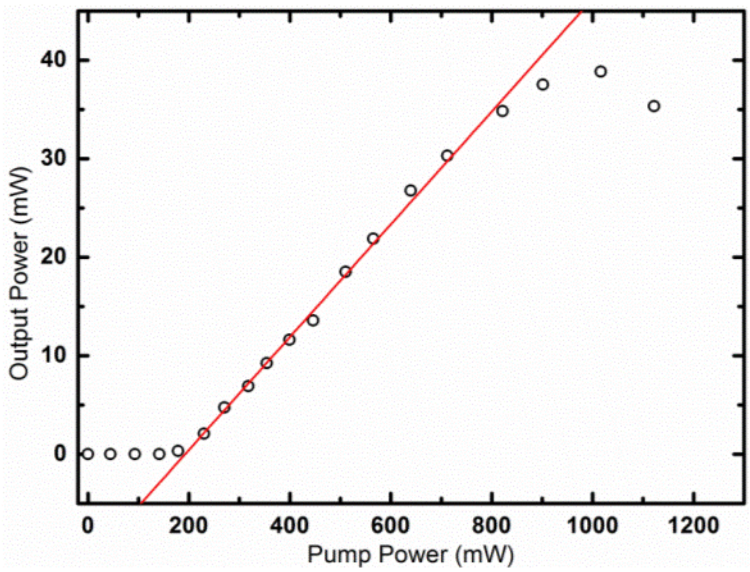

Figure 17. Laser output power as a function of pump power using a 70% reflectivity output coupler. Slope efficiency from fitted line is 5.7%.

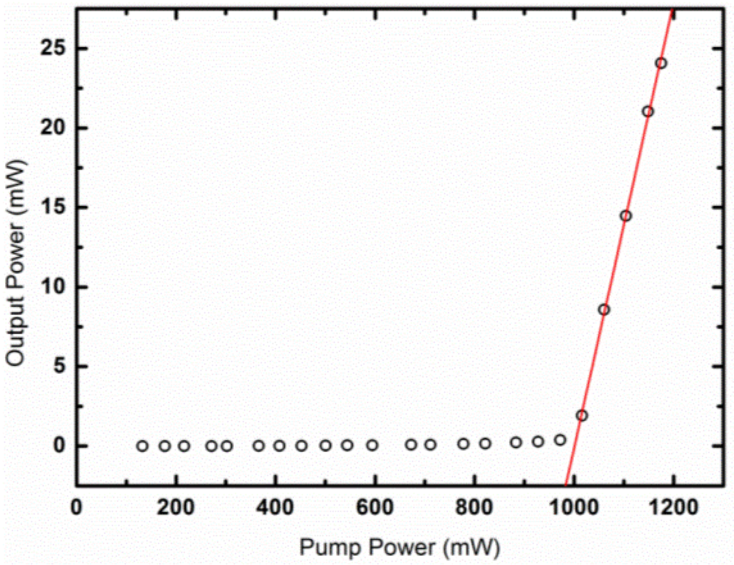

Figure 18. Laser output power as a function of pump power with no output coupler. In this case Fresnel reflections of 18% effectively act as the output coupler. Slope efficiency from fitted line is 14.0%.

5.3. Milestone 5: Demonstrate lasing in Cr^{2+}: ZnSe conclusions

Cr^{2+}: ZnSe waveguide laser performance has been significantly improved over a number of key attributes. The maximum achieved slope efficiency was increased by almost a factor of 3 from 5% to 14%. Laser thresholds as low as 190 mW have been demonstrated which opens the door to the fabrication of compact, directly diode pumped, battery operated devices. Large cross-sectional area waveguides have been created that are well suited to high power and pulsed laser operation. These waveguides can be sent to AFRL, Wright Patterson Air Force Base for experiments in to high power applications.

6. Phase 2 – Milestone 6: Regenerative amplifier in Cr^{2+}: ZnSe (1st April 2012 – 30th September 2012).

One application area of key interest is the creation of an integrated regenerative amplifier based on Cr^{2+}:ZnSe. A regenerative amplifier allows for very high gain of a seed pulse (typically around 10^6 [27]), from nJ level up to mJ level. They operate by coupling a seed pulse into a cavity containing an optical amplifier, the pulse is allowed to circulate, gaining energy from the amplifier, until it is coupled out many cavity roundtrips later. It should be noted that typically average power is not significantly increased by the regenerative

amplifier, but repetition rate is lowered and the pulse energy can be increased significantly. Key components to consider in the design of an integrated optical regenerative amplifier are the optical modulator and the optical amplifier.

6.1. Single pass amplifier gain

Prior to the design of any complicated multipass amplifier, the single pass amplification properties of the waveguides had to be investigated. Using a co-propagating 2300 nm laser diode and 1928 nm thulium fibre pump laser the internal gain of the waveguides was measured. By measuring the signal transmitted through the waveguide with no pump present and comparing this to the signal when the pump power is varied a value for the internal gain can be calculated. For this value to be correct, the fluorescence without incident signal was recorded at each pump power increment. Equation 1 describes this signal-fluorescence-gain measurement:

$$Internal\ Gain = \frac{(SFG - Fluorescence)}{Signal\ without\ pump} \qquad \textit{Eq. 1}$$

where SFG is the total output power from the waveguide with incident pump and signal and all power measurements are taken at the waveguide output. Both the pump and signal modes supported by the waveguide are shown in Figure 19.

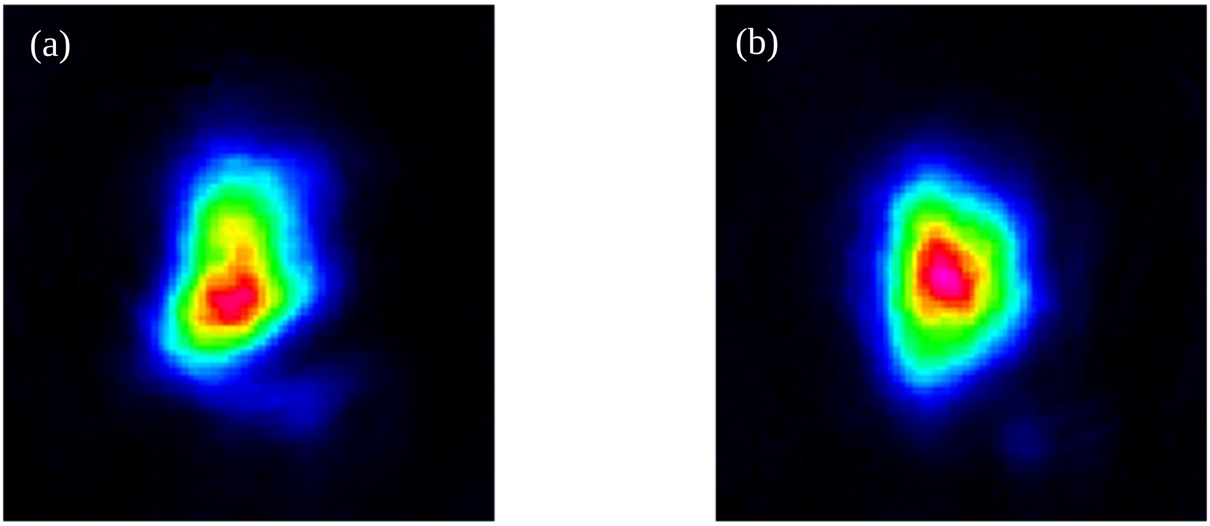

Figure 19. Near field image of (a) 1928 nm pump mode and (b) 2300 signal mode supported by the waveguide.

The internal gain measurements were taken at a range of temperatures from 10 – 30° C in order to investigate any possible thermal changes to the gain properties of the material such

as fluorescence lifetime quenching [1]. The temperature control was performed by mounting the crystal with thermal paste to a water cooled copper heat sink, the heat sink temperature was varied with a PID controlled recirculating chiller. The results are plotted in Figure 20.

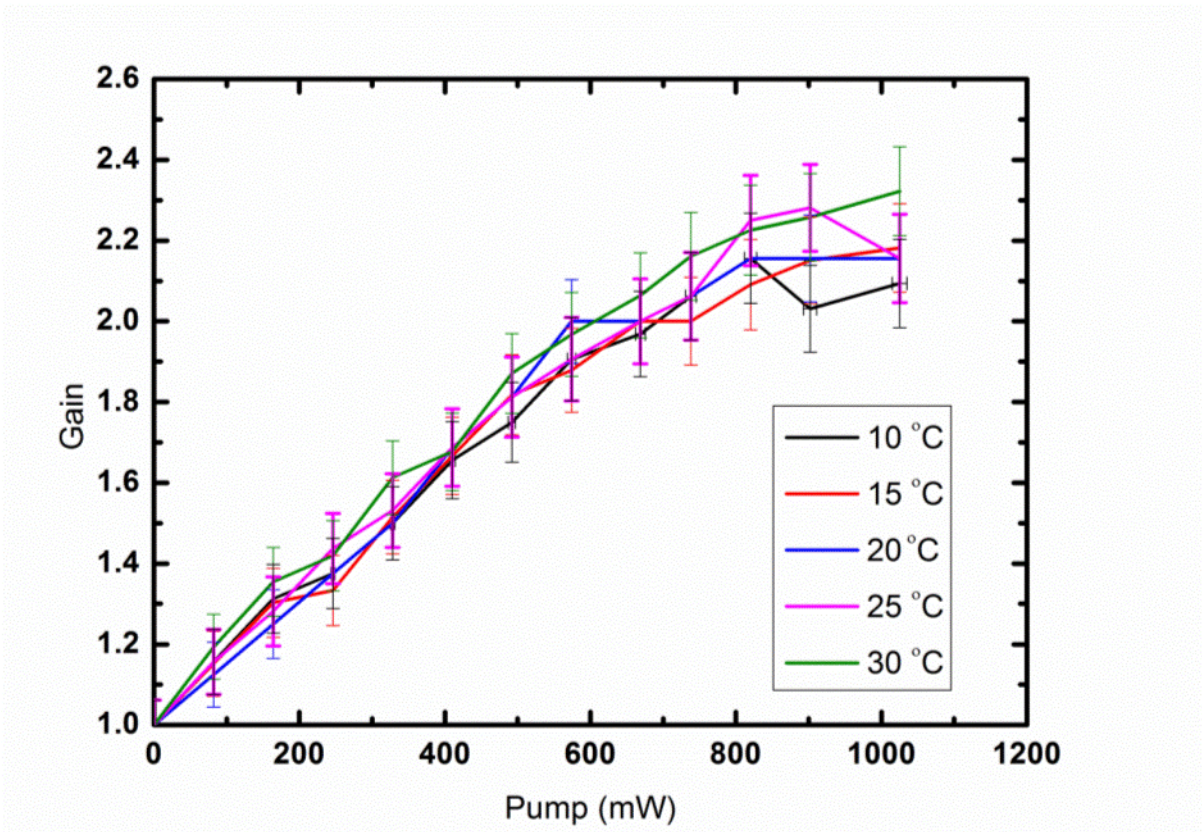

Figure 20. Internal gain of the waveguide for varying incident pump at different temperatures showing any temperature dependence is within our measurement error.

The results showed a maximum of 2.2X internal gain (3.4 dB) for a 6 mm waveguide with temperature showing no discernible effect. However, this is most likely due to the limited temperature range investigated.

6.2. Multipass amplifiers

A channel waveguide configuration limits the design of multipass amplifiers because of the inability to spatially offset or angle different passes of radiation through the cavity, for this reason, only collinear schemes can be considered. Double pass amplification will be considered in future reports, however here we will look at some of the difficulties in fabricating a regenerative amplifier. Of key importance in the design of the regenerative

amplifier are the optical modulator characteristics. The modulator must be fast in comparison to both the seed laser round trip time and the regenerative amplifier round trip time. If we desire a compact amplifier (~25mm length for a standing wave cavity), then round trip times are of the order of 500 ps. This requires a multiple GHz amplitude modulator. Also of importance is the loss characteristic of the modulator, since the light circulates through the modulator on each round trip, losses must be low. Guided mode electro-optic modulators in single crystal ZnSe are assigned for investigation in Phase 5, Milestone 12 Electro-Optic Modulator/Switches in ZnSe.

6.3. Milestone 6: Regenerative amplifier in Cr^{2+}: ZnSe conclusions

Significant development of the gain element has occurred since the last annual report with the demonstration of an internal gain of 3.4 dB for the 6 mm device (see Section 6.1). Mathematical models based on Berry *et al.* [5], show agreement with these CW results and work is underway to investigate pulsed operation.

The design and fabrication of an integrated cavity regenerative amplifier will be revisited after the successful fabrication of a low loss electro-optical modulator following Phase 5.

7. Summary and conclusions

Over the past year, channel waveguide technology in ZnSe and Cr^{2+}: ZnSe has undergone major advancement from initial low loss guiding in the near-infrared to mid-infrared with single or multimode behaviour. These structures have been used in waveguide cavities and provided the first demonstration of a channel waveguide laser, paving the way to the development of high power, compact and robust Cr^{2+}: ZnSe sources. Initial results of 5% slope efficiency and 18.5 mW outputs have already been improved by almost a factor of 3 to 14% and 43 mW and far greater performance is expected through waveguide optimisation and access to greater pump powers. Single pass amplifier internal gain has been measured at 3.4 dB with maximum performance only limited by the available pump power (1.2 Watts).

The results contained in this report complete Phase 2 of the project with a number of successful outcomes, realising compact, channel waveguide sources in Cr^{2+}: ZnSe. This sets solid foundations for the project to progress to Phase 3 and the development of high power, robust mid-infrared waveguide sources for real world applications.

8. Publications and forthcoming publications

Title	Lead Author/Presenter and Description	Journal/Conference
Ultrafast Laser Inscription of Near Infrared Waveguides in Polycrystalline ZnSe.	**Mr. John R. Macdonald** Report of first channel waveguides in ZnSe.	Optics Letters 2010 Volume **35**(23) Pages 4036-4038.
Ultrafast Laser Inscription of Waveguide Structures in Cr2+:ZnSe.	**Mr. John Macdonald** Report of first channel waveguides in Cr^{2+}: ZnSe supporting guiding in the near infrared.	OSA Advances in Optical Materials Conference Proceedings February 2011. Paper AIFB5
Directly Written Mid-Infrared Waveguides in Zinc Selenide.	**Mr. John R. Macdonald** Report of first mid-infrared channel waveguides in ZnSe	OSA Advances in Optical Materials Conference Proceedings February 2012. Paper IF1A.3
Fabrication of Active Waveguides Using Femtosecond Lasers	**Prof. Ajoy K. Kar** Review of significant research conducted in Heriot-Watt NLO group	**Invited** OSA Advances in Optical Materials Conference Proceedings February 2012. Paper IF1A.1
Ultrafast laser inscription of photonic devices for integrated optical applications Stephen J. Beecher	**Dr. Stephen J. Beecher** An introduction to ultrafast laser inscription and a summary of recent technological advances	**Invited** A new paradigm of science driven by ultrafast lasers. Royal Society of Edinburgh Edinburgh, UK. February 2012
Ultrafast Laser Inscription – Science Today Technology Tomorrow	**Prof. Ajoy K. Kar** Update on recent progress in the field and expected impact on future technology	**Invited** ICOOPMA 2012, Nara, Japan June 2012 Paper 3B3-3, ID 1299
Light-Matter Interactions: Applications in Photonics and Biophotonics	**Prof. Ajoy K. Kar** Review of highly flexible nature of ultrafast laser inscription technology and	**Invited** ICPEPA 2012, University of Rochester, USA

	its wide range of applications	August 2012 Paper TrC 14
Mid-infrared photonics enabled by 3D laser writing chalcogenide glass	**Prof. Ajoy K. Kar** Progress in mid-infrared photonic devices fabricated or enabled by ultrafast laser inscription	**Invited** SPIE Security + Defence, Emerging Technologies Edinburgh, UK. September 2012. Paper 8542-48

The first report of lasing in a Cr^{2+}: ZnSe channel waveguide is currently under consideration for publication in Nature Photonics journal. After this initial report there are a number of publications prepared for submission. The details of these forthcoming papers are listed below:

Title	Description	Journal
Mid-Infrared Cr: ZnSe Channel Waveguide Laser.	First report of lasing in Cr^{2+}: ZnSe channel waveguide laser.	Nature Photonics Submitted September 2012
Compact Cr: ZnSe Mid-infrared Oscillator.	Improved performance and full characterisation of the laser as described in Section 5.2 will be reported.	Optics Letters To be submitted 2012
Compact Cr: ZnSe Mid-infrared Amplifier.	Amplification performance of the current waveguides as described in Section 6.1.	Optics Letters To be submitted 2012
Localised Refractive Index Modification of ZnSe for Photonic Devices.	The use of direct laser inscription to achieve a positive or negative refractive index change in ZnSe will be reported. This will focus on the potential for applications in integrated photonic devices such as couplers, modulators and Bragg gratings.	Advanced Materials To be submitted 2012

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Appendix A – March 2012 Interim Report

FA8655-11-1-3001 - Interim progress report

March 2012

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This project aims to develop compact, directly written photonic devices in Cr^{2+}: ZnSe using ultrafast laser inscription (ULI) technology. Building on previous work on mid infrared waveguides in ZnSe [1], structures have been fabricated in Cr^{2+}: ZnSe which have demonstrated lasing at 2572 nm. This is the first demonstration of a directly written Cr^{2+}: ZnSe waveguide laser and an important milestone for the development of high power (>20W), compact and robust Cr^{2+}: ZnSe laser sources.

1.1 Introduction

Mid infrared laser sources in the 2-5 μm region are required for range of academic, commercial, medical and military applications such as non invasive imaging, laser surgery, remote sensing and infrared countermeasures. Chromium doped II-VI semiconductors such as Cr^{2+}: ZnSe, Cr^{2+}: ZnS and Cr^{2+}: CdSe have demonstrated many of the required properties for such applications [2-5] with Cr^{2+}: ZnSe in particular demonstrating high power pulsed or CW operation (> 10W) and wide tunability of 1973-3339 nm[6-8]. Despite these promising developments, the power scaling of Cr^{2+}: ZnSe lasers has long been hindered by the high thermo-optic coefficient of the material (70×10^{-6} K^{-1}) [9]. An attractive solution to this problem would be to utilize waveguide technology to make the system immune from such detrimental thermo-optic effects.

2.1 Mid Infrared Waveguides in ZnSe and Cr^{2+}: ZnSe

Mid-infrared waveguides have previously been demonstrated in undoped ZnSe with low propagation losses and single mode guiding at 3.39 μm [1]. Figure 1 shows the cross-section of one such waveguide and its associated mode at 3.39 μm. With these optimized inscription

parameters, waveguides were fabricated in a Cr^{2+}: ZnSe sample. However, upon observation it was evidentthat the resultant structures differed from those fabricated in the undoped material. The modification of the Cr^{2+}: ZnSe material appeared to be less than that obtained in the undoped ZnSe and the horizontal components of the structure were extremely weak. A comparison of the two structures is shown in Figure 2.

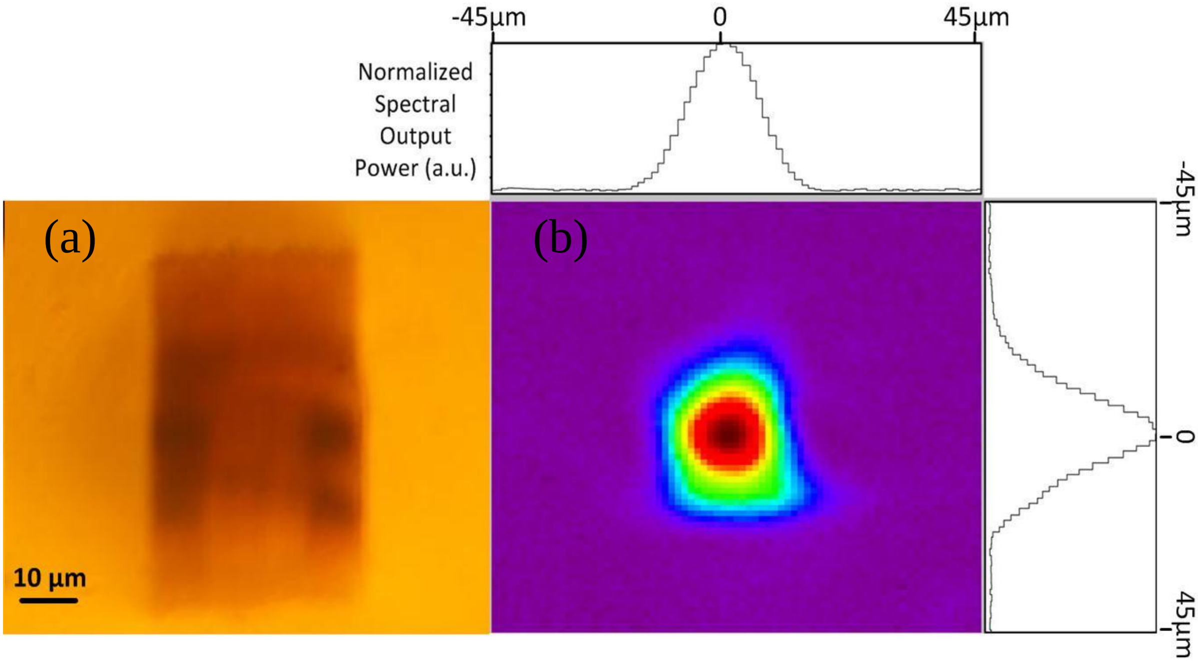

Figure 1. (a) Waveguide end facet cross-section (b) false color intensity profile of associated mode at
3.39 µm. Field of view is 90 x 90 µm.

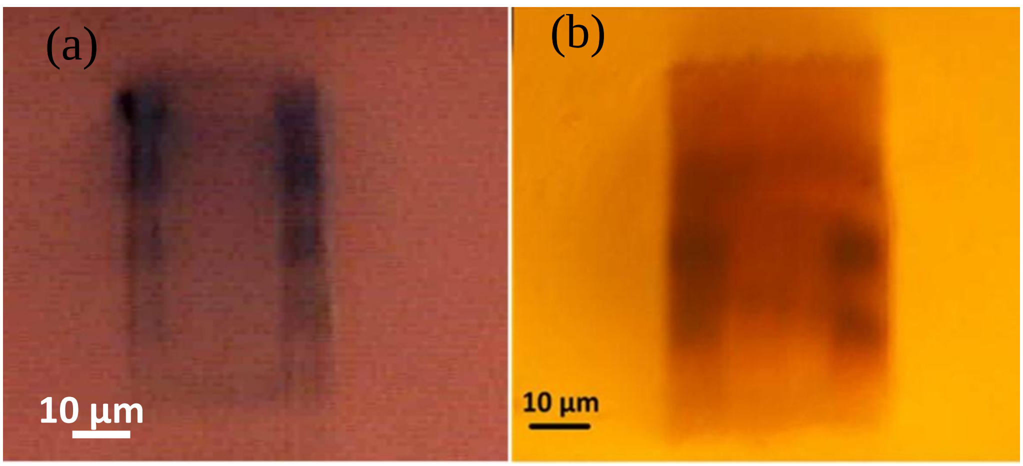

Figure 2. Waveguide end facet cross-section of structures written with the same inscription parameters in (a) Cr^{2+}: ZnSe and (b) undoped ZnSe. Field of view of both images is 90 x 90 µm.

In order to compensate for this difference in modification it was necessary to optimize parameters for the doped material.

2.2 Parameter Optimization

Waveguides were inscribed in Cr^{2+}: ZnSe using the same method as described in section 2.1 however the resultant structures were observed to guide only in the horizontal axis. Upon closer inspection modification in Cr^{2+}: ZnSe appeared to be less compared to that fabricated with the same parameters in undoped ZnSe. Figure 3 shows the different structures obtained in ZnSe and Cr^{2+}: ZnSe, written with the same inscription parameters.

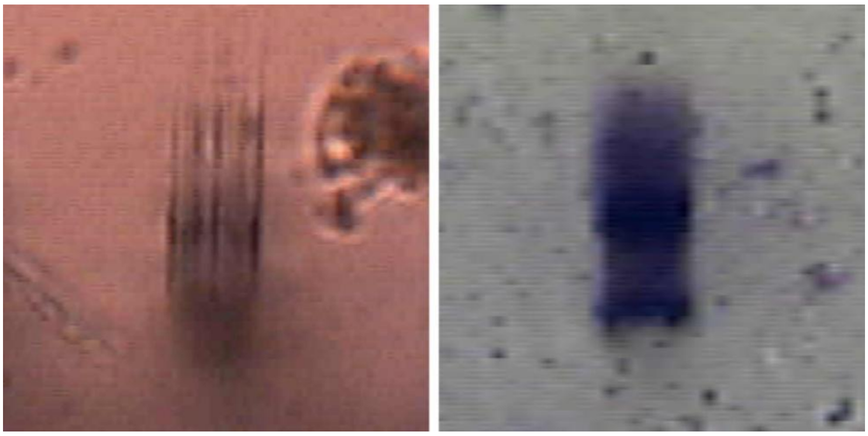

Figure 3. Modification comparison. (a) Cr^{2+}: ZnSe (b) ZnSe. Field of view 100 x 100 µm.

By visually comparing the extent of the modification at various paramaters a suitable parameter set was chosen for fabrication in Cr^{2+}: ZnSe. After fabrication the sample was ground and polished to remove any tapered sections towards the ends of the waveguides.

3.1 Cr^{2+}: ZnSe Waveguide Laser Operation

The sample was mounted in the pump laser setup, as shown in Figure 4, with a dichroic input mirror and a 1% ouput coupler butt coupled to either end facet of the waveguide.

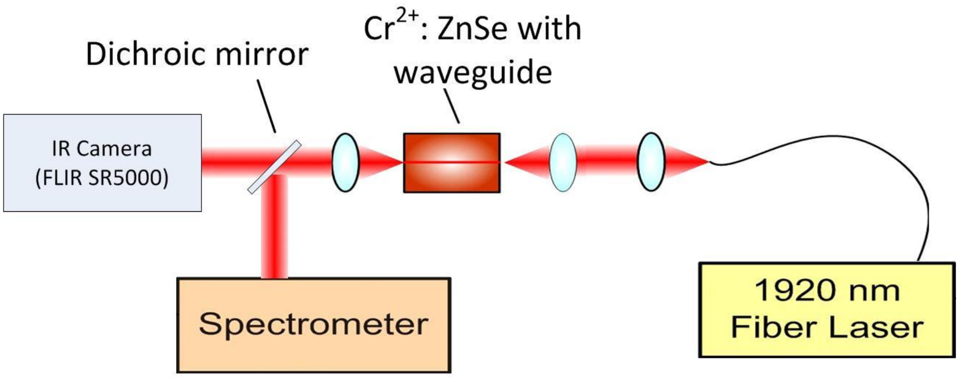

Figure 4. Cr^{2+}: ZnSe waveguide laser experimental setup.

The waveguide was then pumped with the 1928 nm thulium fiber laser (AdValue Photonics) and the output observed using an infrared camera (FLIR SC7000) and a monochrometer (Zolix Omni-λ300). Figure 5 shows the waveguide end facet with associated modes at the pump and output wavelengths of 1928 nm and 2572 nm respectively.

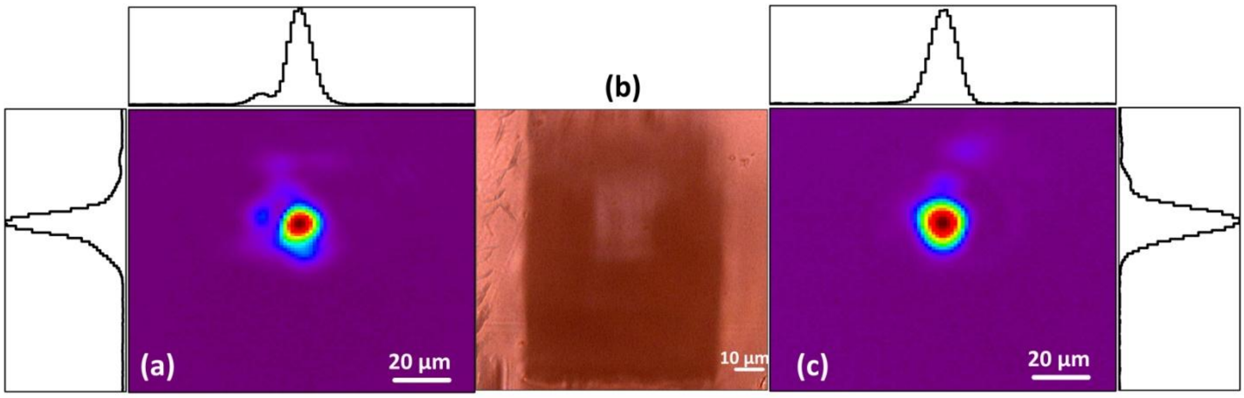

Figure 5. (a) 1928 nm pump waveguide mode (b) waveguide end facet cross-section (c) 2572 nm laser output mode.

It can be seen that both pump and laser output wavelengths are supported in a single mode allowing for good mode overlap with the pump light. The laser output displays a near symmetric 2-D Gaussian mode profile and a mode field diameter of 16.6 x 20.9 (±0.6) µm. The mode field diameter of the pump light is 13.8 x 17.7 (±0.6) µm. Figure 6 shows the spectrum of the laser output with a peak at 2572 nm and a linewidth of FWHM = 3.1 nm.

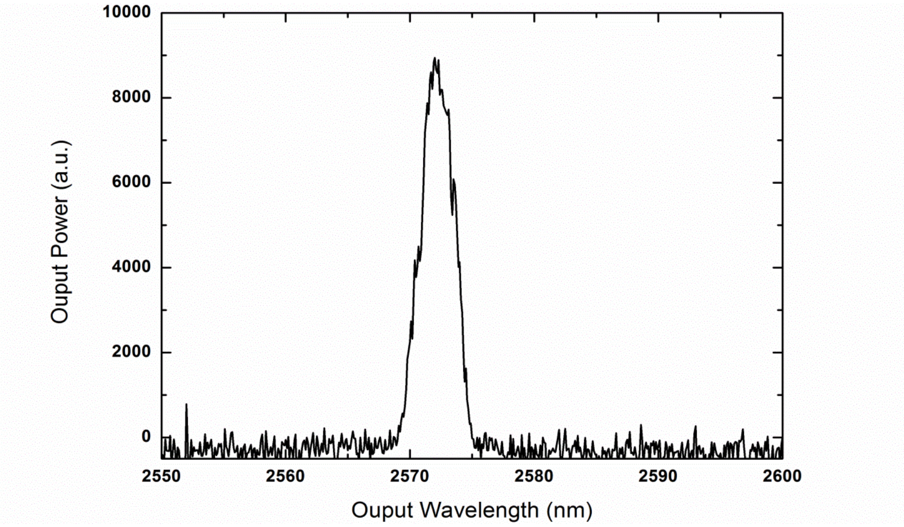

Figure 6. Laser output spectrum with peak at 2572.1 nm. FWHM of the peak is 3.1 nm

The input/output characteristics of the laser were measured using a chopper to duty cycle the pump laser. This was to minimize variations in the coupling losses due to thermal expansion of the Cr^{2+}: ZnSe material. Figure 7 displays characteristic laser threshold behavior of the system.

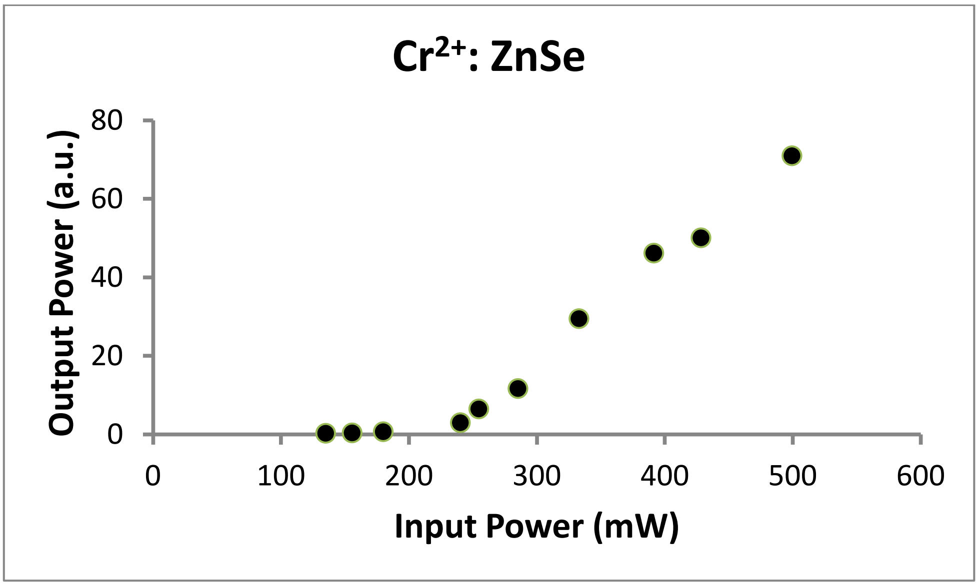

Figure 7. Input/Output graph displaying laser threshold behavior.

4.1 Conclusions

Ultrafast laser inscription has been used to fabricate a mid infrared waveguide laser in Cr^{2+}: ZnSe. Laser operation was demonstrated at 2572 nm with a single mode output displaying a near symmetric 2-D Gaussian mode field distribution. Future work will include the further characterization of the waveguide laser with reconstruction of the cavity using a range of

different output couplers. The amplification characteristics of the waveguide will be investigated allowing structures capable of pulse amplification to be developed. The optimization and full characterization of these waveguides will also allow work to begin on producing a compact, modelocked Cr^{2+}: ZnSe laser.

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Appendix B – June 2012 Interim report

FA8655-11-1-3001 - Interim progress report

June 2012

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Abstract

Lasing has been demonstrated in Cr^{2+}: ZnSe channel waveguide for the first time to the author's knowledge. Laser output at 2486 nm has been demonstrated and initial slope efficiencies have been substantially improved upon, increasing from 2.5% to 14%. Furthermore, large cross-sectional area channel waveguides have been designed and fabricated for use as high power mid-infrared amplifiers.

Introduction

This project aims to use ultrafast laser inscription technology to develop mid-infrared waveguide laser devices in Cr^{2+}: ZnSe with a view to power scaling current chromium laser technologies.

The mid-infrared region (2-5 μm) of the spectrum spans important atmospheric transmission windows as well as many organic and inorganic chemical absorption lines. Consequently, laser sources in this wavelength range are of great importance for military, medical and scientific applications such as infrared countermeasures, laser surgery and remote sensing. Chromium doped II-VI semiconductors, particularly Cr^{2+}: ZnSe, have demonstrated many of the desired properties for such applications including wide tunability [1], room temperature operation [2], narrow linewidth output, and power output over 10 Watts in both pulsed and CW operation [3,4]. However, the power scaling of Chromium lasers has long been hindered by the high thermo-optic coefficient of the host material. Thermal lensing in the laser gain medium leads to cavity instability or optical damage limiting current Cr^{2+}: ZnSe lasers to less than 20 W of output power [4]. Waveguide geometry offers an attractive solution to this problem by avoiding the detrimental thermal lensing effect. [5]

Depressed cladding Cr^{2+}: ZnSe Waveguides

To date, this project has demonstrated the laser operation of a Cr^{2+}: ZnSe channel waveguide featuring a depressed cladding structure. The waveguide core was composed of unmodified Cr^{2+}: ZnSe which was surrounded by a region of material whose refractive index had been decreased by laser irradiation. Initial waveguides using this design had propagation losses which were too high for laser threshold to be reached. Much of this loss was believed to be due to tunnelling of the waveguide mode from the waveguide core into the bulk material. To reduce propagation losses due to tunnelling another region of material was irradiated, further reducing the material refractive index. This resulted in a waveguide composed of a core surrounded by a region of slightly reduced refractive index which in turn was surrounded by a region of further reduced refractive index, see Figure 1. This design features many of the benefits of a low refractive index contrast waveguide, such as single mode like performance and low scattering, but with reduced tunnelling losses.

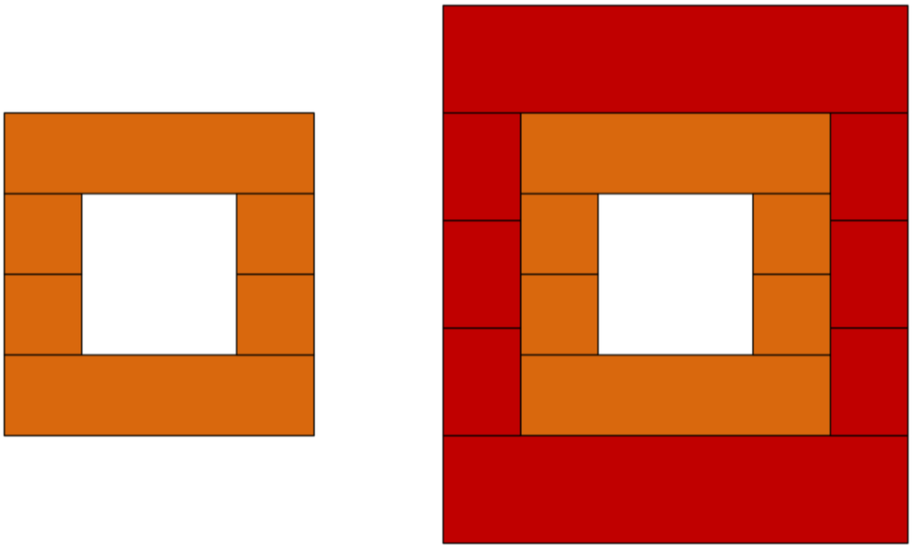

Figure 1. A schematic of (Left) a single clad and (Right) a double clad depressed cladding waveguide where the red color represents a greater change in refractive index than orange.

With this waveguide design losses were reduced sufficiently for laser threshold to be reached and a maximum output power of 17.5 mW was achieved for 1.2 W of incident 1920 nm pump power. Laser threshold was occurred at 720 mW as shown in Figure 2. This is to the best of our knowledge the first channel waveguide laser to be demonstrated in Cr^{2+}: ZnSe and represents the achievement of one of the major milestone of this project.

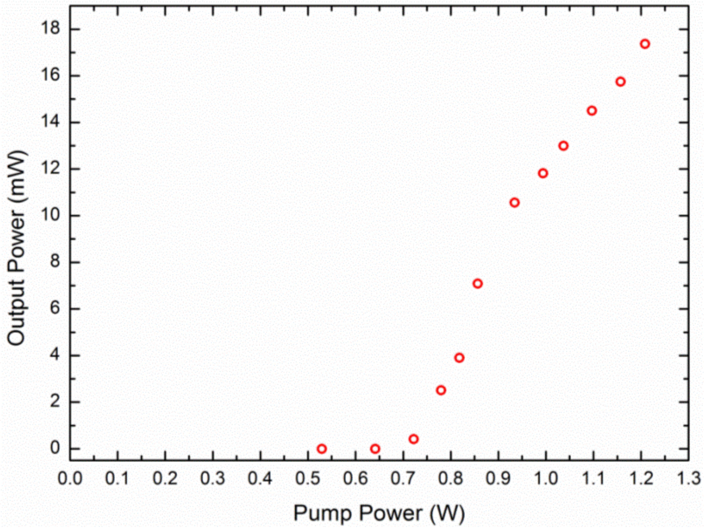

Figure 2. The input-output characteristics of the first laser inscribed Cr^{2+}: ZnSe waveguide laser operating with an 80% reflectivity output coupler.

It can be seen in Figure 2 that there are two distinct slopes for the laser output. This is thought to be caused by thermal effects altering the coupling of pump light into the waveguide. The slope efficiency for pump powers beyond 900 mW was measured to be 2.5%.

Inspection of this double clad, depressed cladding, waveguide with an optical microscope shows signs of cracking in and around the structure. Most of this cracking does not intersect the waveguide core but is likely to contribute significantly to the propagation losses of the waveguide. Figure 3 presents a white light transmission micrograph of the waveguide with signs of micro-cracking clearly visible.

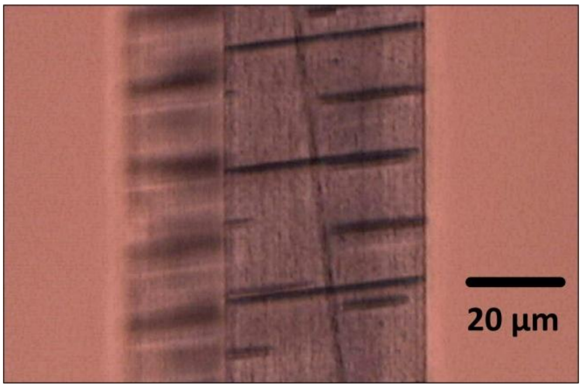

Figure 3. Optical micrograph of waveguide structure showing cracking. Image was taken with white light transmission normal to the waveguide propagation direction, which runs from bottom to top in the image.

Circular depressed cladding structures

Several techniques have been investigated since the last report to reduce the micro-cracking in the waveguide structures. Many design variables exist for the double clad structures but improvement on the laser performance presented in figure 2 has been limited. In parallel with optimization of these structures several alternative designs have been investigated. Circular cross-section depressed cladding structures have previously been demonstrated in other crystalline and polycrystalline laser mediums [6, 7] exhibiting propagation losses lower than 0.5 dB·cm^{-1} and 2 dB·cm^{-1} respectively. In previous demonstrations, single scans of the

substrate through the laser focus were used to inscribe each element of the circular depressed cladding. Parameters to achieve sufficient refractive index modification to achieve low loss guiding for this waveguide class have not been identified, but utilizing multiple over-scans the required material modification can be achieved. This has allowed waveguides to be fabricated by inscribing a ring with a localized reduction in refractive index, as presented in Figure 4.

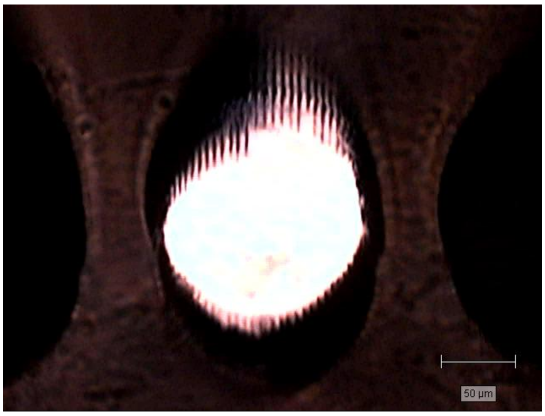

Figure 4. Optical micrograph of circular cross-section depressed cladding waveguide. Waveguide is shown guiding white light from microscope illumination. This structure has a diameter of 150 µm.

These structures were inscribed with diameters ranging from 40 to 150 µm and consisted of 40 or 80 individual inscription elements as can be seen in Figure 3. The laser cavity was then constructed by butt-coupling a dichroic mirror on the pump input side of the waveguide and an output coupler mirror on the opposite side. The dichroic mirror was anti-reflection (AR) coated for the pump wavelength and highly reflective for 2050 -2430 nm. The laser operation of the waveguide was then tested with 80% and 70% reflectivity output couplers coated for 1700 - 2700 nm and finally with no output coupler. In the case without an output coupler, the Fresnel reflections from the end facet of the waveguide effectively provides an 18% reflectivity output coupler. Figure 5 shows the cavity construction for laser characterisation and the output spectrum.

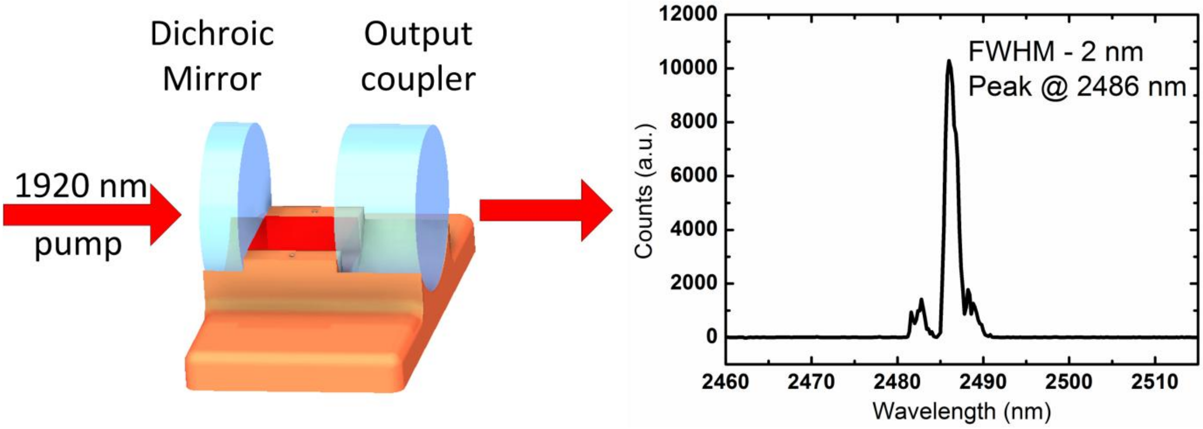

Figure 5. Waveguide laser cavity construction and output spectrum

Laser output at 2486 nm was observed in the 80 µm diameter structures and showed horizontal polarization relative to the optical bench. Figures 6-8 show the laser ouput power

as a function of pump power with the 80%, 70% and 18% (Fresnel reflections from end facet) reflectivity output couplers respectively.

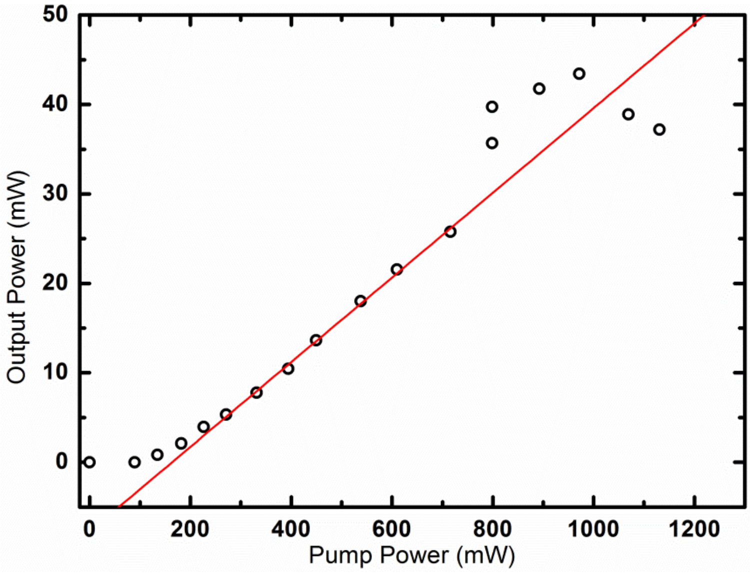

Figure 5. Laser output power as a function of pump power using an 80% reflectivity output coupler. Slope efficiency from fitted line is 4.7%.

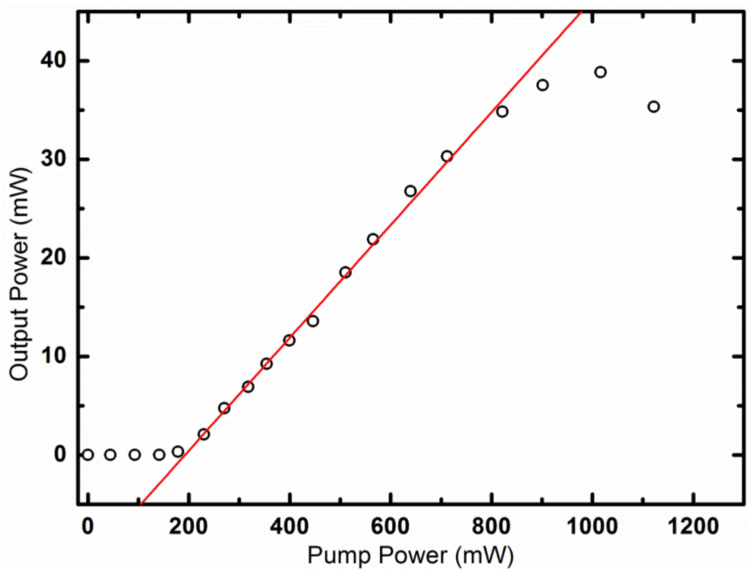

Figure 6. Laser output power as a function of pump power using a 70% reflectivity output coupler. Slope efficiency from fitted line is 5.7%.

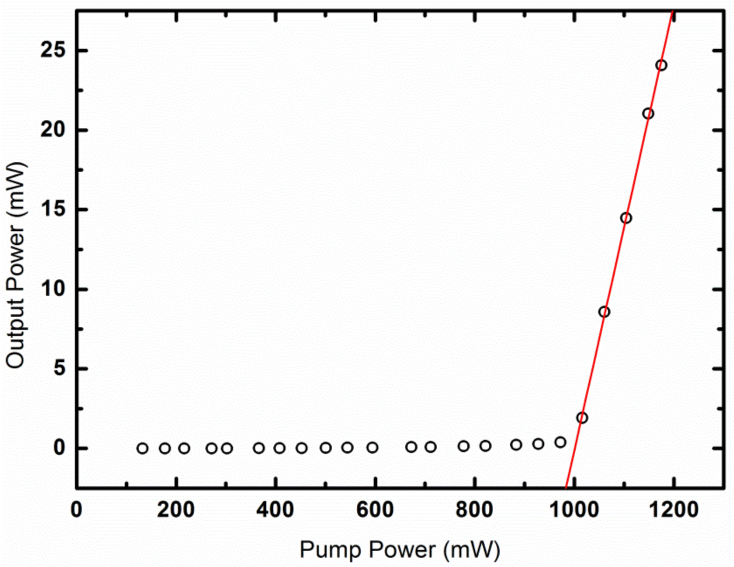

Figure 7. Laser output power as a function of pump power with no output coupler. Fresnel reflections effectively provide an 18% reflectivity output coupler. Slope efficiency from fitted line is 14.0%.

The maximum slope efficiency was observed without an output coupler and was 14% however the maximum power output of 43.4 mW was recorded with the 80% reflectivity output coupler. The lasers constructed with both the 80% and 70% reflectivity output couplers show signs of the efficiency decreasing for high pump powers, this however is not observed for the laser featuring no output coupler within the pump power available. As a result, additional pump power would likely provide a higher output power from this configuration.

With the pump power available from our thulium fiber laser, 1.4 W, we could not achieve threshold for the larger diameter structures of 150 µm. These are expected to have lower propagation losses [8] and higher saturation powers, so may prove suitable for high power amplifiers when pumped with sufficient power.

Conclusions

Laser oscillation has been demonstrated in depressed cladding Cr^{2+}: ZnSe waveguides. Circular cross-sections and thick walled double clad structures have been investigated and significant performance improvements have been made since our last report. Slope efficiencies have improved by more than 5x from 2.5% to 14% and further optimisation of waveguide fabrication is expected to yield even better performance. A current maximum output power of 43 mW has been demonstrated for 1 W of pump power showing an improvement in optical-to-optical efficiency from 1.4% at the time of our last report to 4.3%. Large area circular structures, despite exhibiting higher thresholds, are likely to provide better performance at high powers, either directly as oscillators or as power amplifiers.

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